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NRL Report 5575

THE SPACE SURVEILLANCE SYSTEM

A SUMMARY REPORT
[UNCLASSIFIED TITLE]

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Applications Research Division

NO_X

October 31, 1960

CONTENTS

ABSTRACT
[Confidential]

The Naval Research Laboratory proposed the Space Surv il-lance System for detecting, tracking, and orbit predicting of non-radiating satellites. The Advanced Research Projects Agency has supported a feasibility experiment as Phase I, which has been completed. Further research and development in the area covered by this System are proceeding. Currently this System provides the only operational capability the Country has to detect noncooperating unannounced satellites.

The performance of the experimental system on typical satellites is illustrated. Coverage extends to about 450 statute miles in height on one-square-meter targets over limited sections of an east-west line. The second phase of the program, now in the development stage, will provide coverage to a height of about 2500 miles with a probability of detection of 95 percent over the extent of the entire line from the east to the west coast. Also automatic processing of data is to be incorporated to provide a system suitable for operational use. A fully operational system requires a second line to enable precise orbit determination in a single pass. A recommended location is on a line extending in a northwest-southeast direction across the United States. The flexibility of the system design permits extensions and additions of equipment and facilities to meet increased operational requirements.

PROBLEM STATUS

This is an interim report on the problem, serving to bring up to date the description and performance previously presented in NRL Report 5419, October 1959. This problem has been supported by the Advanced Research Project Agency. It was transferred to the Navy by Amendment No. 9 dated October 18, 1960. Work on the problem continues.

AUTHORIZATION

NRL Problem R02-35
ARPA Order No. 7-58

Manuscript submitted October 12, 1960.

THE SPACE SURVEILLANCE SYSTEM

A SUMMARY REPORT
[Unclassified Title]

BACKGROUND

The launching of Sputnik II came about a month after Sputnik I, and then reports circulated that the Russians intended to launch satellites at a rate of one a month during the IGY. When Sputnik III did not appear after several months, there was concern in the Department of Defense that a satellite might have been launched but was not announced. It was thus evident that this Country needed a system to detect and determine the orbits of unannounced, nonradiating satellites. The possibility of an enemy using his own satellites to determine the position of our Fleet made this problem of special interest to the Navy.

The concept of a system needed for this purpose was devised by Naval Research Laboratory personnel in February 1958. Based on this concept a proposal was made to the Advanced Research Projects Agency in May 1958 with the result that ARPA Order 7-58 of June 20, 1958, was issued to the Laboratory to develop Phase I of the proposed system. The first portion of the system operated on July 29, 1958, and the first confirmed reflected satellite signal was obtained on August 7, 1958.

The experimental system, as built, consists of two Complexes of three stations each. The complete Eastern Complex was made operational in November 1958; the Western Complex in February 1959. The first detected "unknown" was the final stage of Explorer VII (1959 Iota 2) in October 1959; the second unknown was the capsule of Discoverer V (1959 Epsilon 2), detected in February 1960.

The experimental system as now operating, and designated as Phase I, can detect objects of one-square-meter radar cross section to heights of about 450 statute miles. Improvements to this system required for detection to heights of 2500 miles with automatic processing of data have been approved for development and are now being implemented as the next phase. Additional installations required for a complete operational system are proposed.

The initial proposal to ARPA conceived that the satellite would be detected by signals being received after reflection from a cw transmitter (Fig. 1). The receivers would measure only (a) the signal amplitude and (b) the angle of arrival vs time. The angular measurements are accurately made using interferometer techniques derived from the Vanguard Minitrack system.[*] With such a system no communications tie-in or time synchronization between transmitter and receiver is required. By observing the satellite at two receiving sites and measuring the two angles of arrival in a single plane the position of the satellite can be computed (Fig. 2). Figure 3 illustrates how the radio interferometer determines accurately the zenith angle giving the direction of the satellite-reflected signal. The various rays travel different distances to the ground antennas. This difference is measured in terms of the wavelength of the signal through comparison of the phase difference between pairs of antennas. The greatest spacing provides the precision, and other spacings permit resolution of ambiguity.

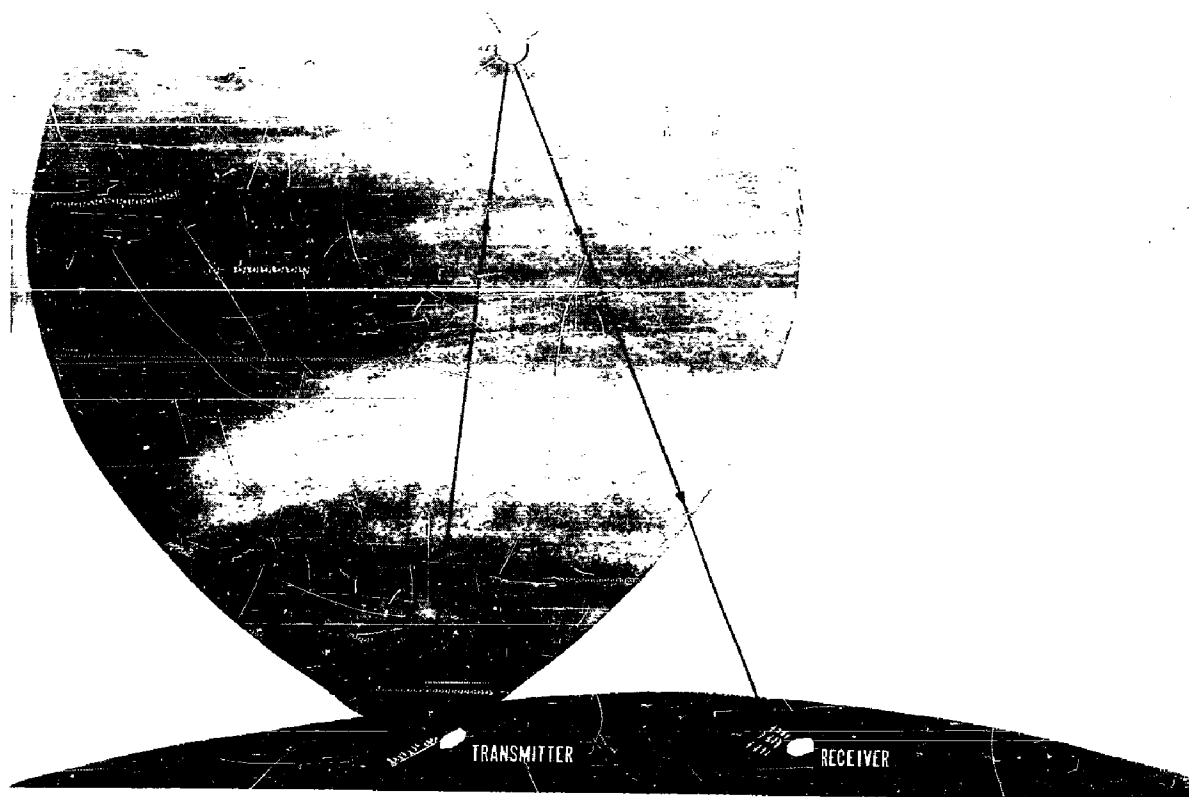[*]John T. Mengel, Proc. I.R.E. 44:755-760, June 1956.

Fig. 1 - Components of the SPASUR system for detection of "dark" satellites
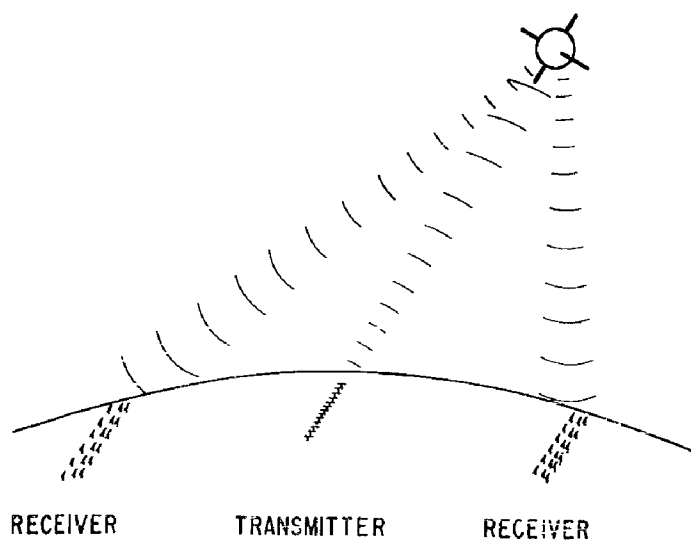

Fig. 2 - A three-station SPASUR complex in which a central transmitter illuminates satellites which reflect radio energy to receivers about 280 miles from the transmitter.
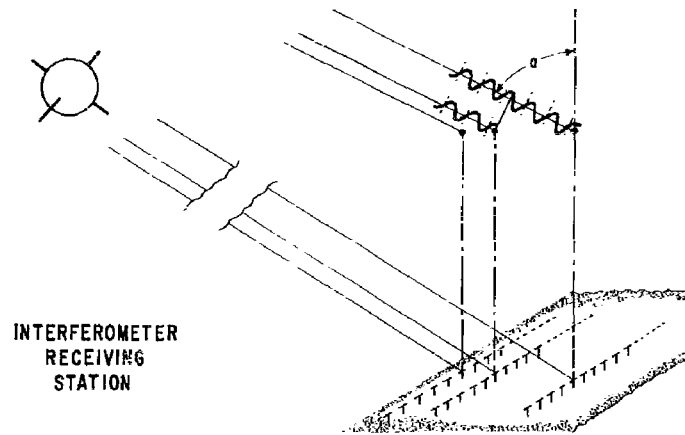
RECEIVER   TRANSMITTER   RECEIVER

Fig. 3 - The interferometer principle for precise measurement of angle of arrival of signals from a satellite

The original proposal included two lines, one built across the southern United States, approximately on the location of the existing experimental system, and the other to be built across the northern United States, permitting orbital looks separated by perhaps 15 degrees as seen from the center of the earth. The complete system as now visualized differs only in detail from this initial conception.

SYSTEM DESCRIPTION

Initially Approved Development

The location of the stations installed for the experimental system is shown in Fig. 4. These stations have been operating 24 hours per day since February 17, 1959. The central stations in each Complex, Jordan Lake and Gila River, are transmitting sites radiating 50 kw at 108 Mc and transmit on antennas 1600 feet long. This power level utilized the largest commercial transmitters available at the time though the need for much higher power was recognized.

The receivers are located about 280 statute miles on either side of the transmitter. The antenna beams of the three stations in a Complex are thin and fan-shaped and overlap in the direction of the "fence." They are narrow in a direction perpendicular to the "fence" and wide in the direction of the "fence." By arranging the stations on a great circle, the two receivers of a Complex can observe some of the passes simultaneously, thus providing data to compute the height by triangulation. By design all six stations are placed on a single great circle so a single transmitter can be used eventually to illuminate the entire system.

Figure 5 is an aerial view of a receiver site. Although 1600-foot ground screens have been provided, only 400-foot antenna sections have been installed at all receiving stations except Fort Stewart, where 1600-foot antennas have been installed for evaluation purposes.

The simplicity of the large antenna installation is shown in the view of Fig. 6. The ground screen consists of aluminum wires stretched over a beam supported by posts approximately seven feet high. One antenna may be seen as the row of small dipoles running down the center of the figure. Other rows are apparent farther to the right.
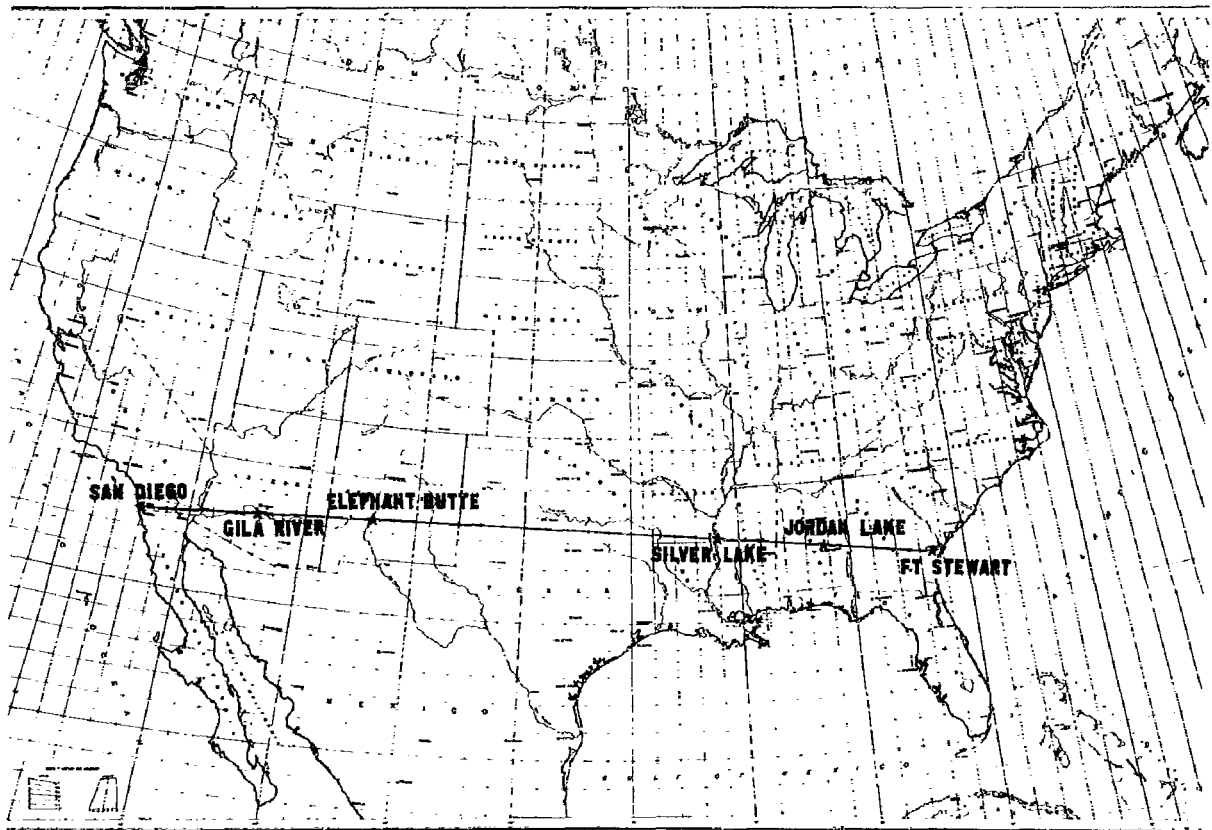
Fig. 4 - Location of the space surveillance stations. Jordan Lake and Gila River are the eastern and western transmitters respectively. The other stations are receivers for the neighboring transmitter.
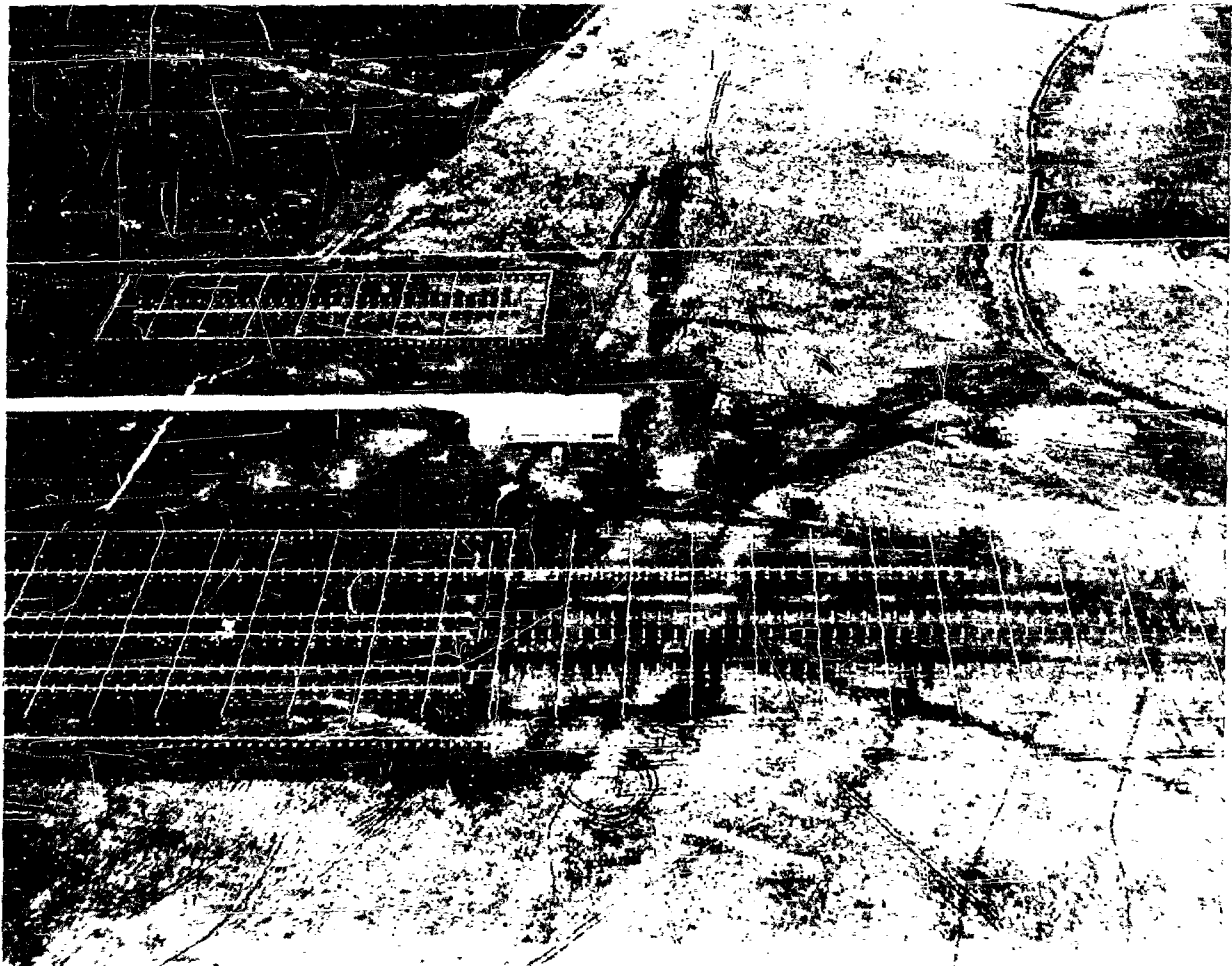
Fig. 5 - Aerial view of a portion of the Silver Lake receiving site
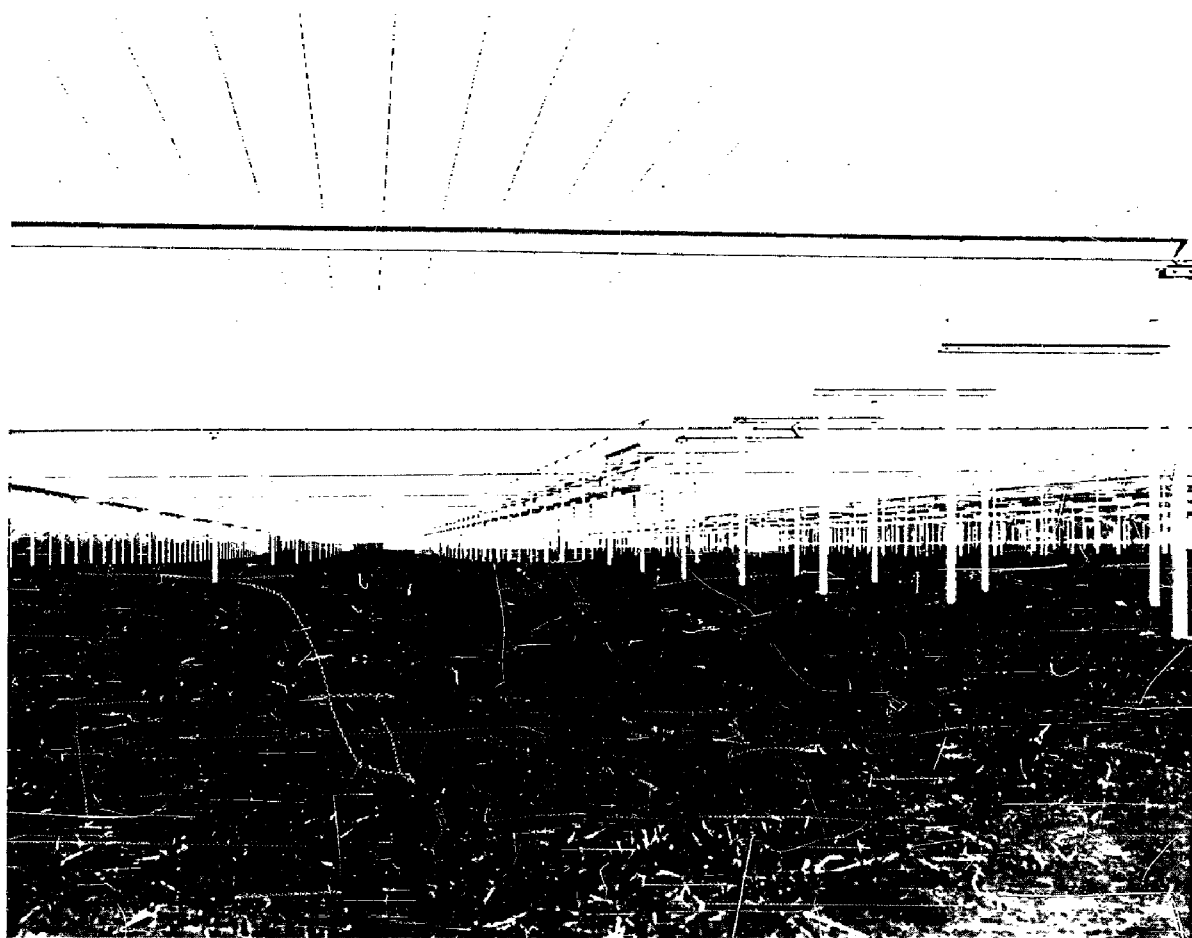
Fig. 6 - Looking up through a receiving station ground screen

Eight channels of output from each receiving station (except 16 at Ft. Stewart) are transmitted over a single phone line to the Operations Center (Fig. 7) at the Naval Weapons Laboratory at Dahlgren, Virginia. Control of the system operation is accomplished from NRL through a teletype network (Fig. 8). At Dahlgren the phone line subcarriers are demodulated, and the data are recorded and analyzed. Data drop-off at NRL permits monitoring and special recording for research and development purposes. Figure 9 shows the record of a signal from one station showing the time code, signal level, and phase recording between various pairs of antennas of the interferometer. The excursion on the phase recordings from minimum to maximum represents 360 degrees of electrical phase. The phase quieting resulting when a satellite penetrates the beam is apparent near the center of this record. Orbit computations and predictions are performed on the NORC computer at the Operations Center. The experimental system has operated as described since October 1959 when eight channels of data from each receiving station became available at the Center.
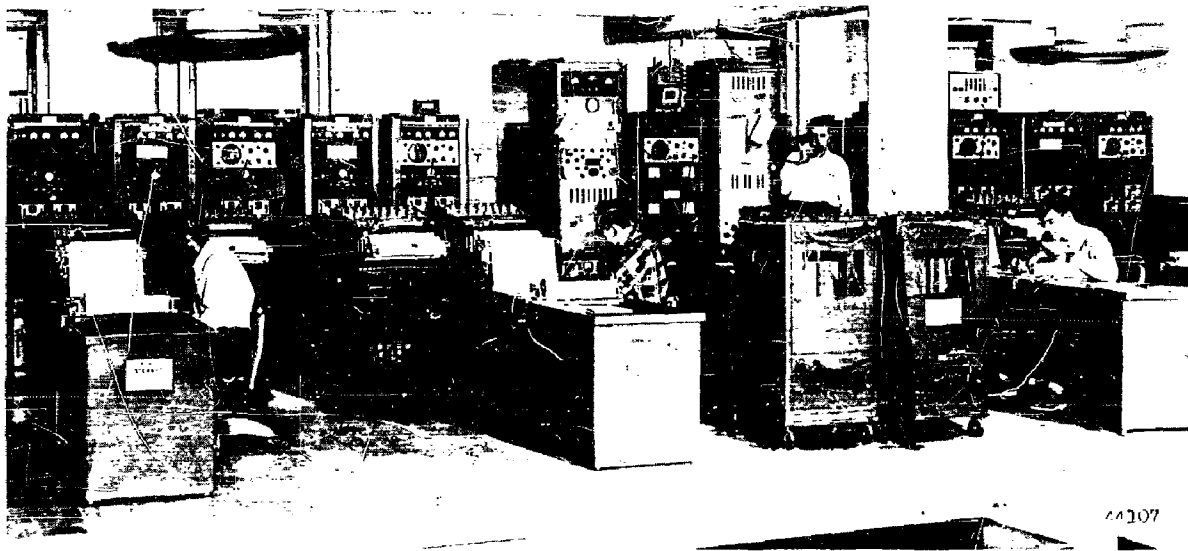
Fig. 7 - SPASUR Operations Center, Dahlgren, Virginia

----- TELETYPE
———— ANALOG DATA

Fig. 8 - SPASUR communications system

400 FT. COLLINEAR ANTENNA SYSTEM

(400 FT) NS PHASE
87.8430 Wavelengths

(521 FT) EW PHASE
114.5860 Wavelengths

(109 FT) EW PHASE
24.0690 Wavelengths

(56.8 FT) EW PHASE
12.4737 Wavelengths

(52.8 FT) EW PHASE
11.5953 Wavelengths

(20 FT) EW PHASE
6.3921 Wavelengths

SIGNAL LEVEL
DISPLAY AGC

SIGNAL LEVEL
NOISE AGC

TIME CODE

PHOTOGRAPH OF SILVER LAKE RECORDING OF THE PASSAGE
OF THE 1958 DELTA 2 (SPUTNIK III) SATELLITE AT 141842.8 Z
MARCH 5, 1960

Fig. 9 - Photograph of Silver Lake recording of the passage of the 1958 Delta 2
(SPUTNIK III) satellite at 141842.8Z March 5, 1960

Improved Single Line

Current research and development will provide major improvements in the existing line. Except for low height coverage, not presently funded, the line will be brought up to a fully operational status including automatic data reduction from satellite detection to orbit computation.

A new transmitter of 500-kw power is being installed at the center of the SPASUR line near Archer City, Texas. This power will be sufficient to illuminate the entire line from east to west coast. It will feed into an antenna one mile long. Eight output amplifiers and a standby driver, each of 62.5 kw, couple to the nine separate sections of the antenna. Any one section may be inoperative without affecting the remaining ones. The driving power is sufficient to increa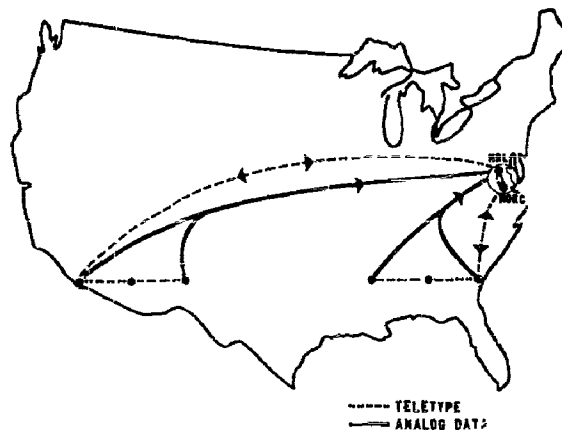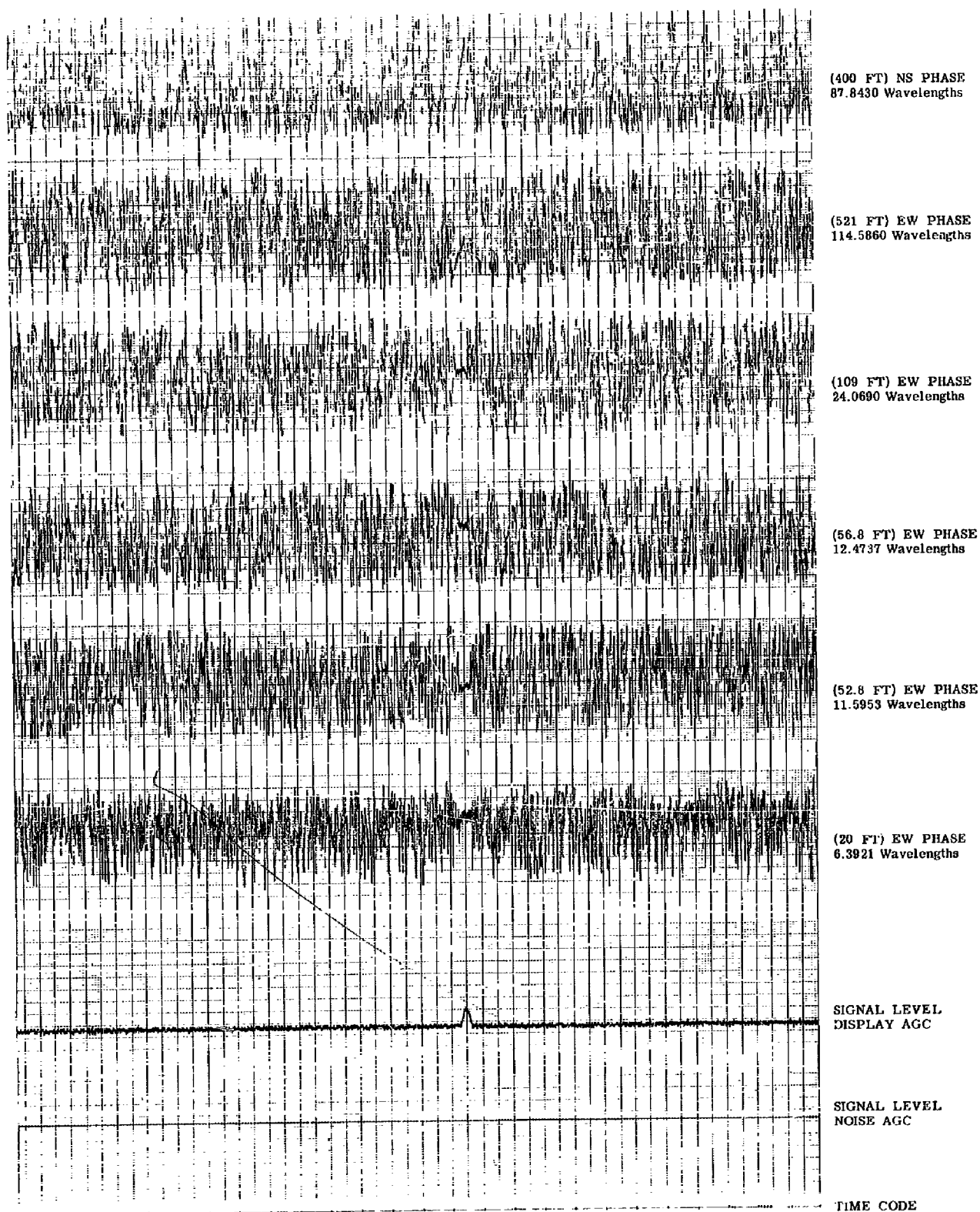se the overall power to one megawatt by adding eight more final amplifiers. This transmitter is expected to be operational about April 1961.

Another development being carried out at the same time will provide an alert and also increase the receiver sensitivity (Fig. 10). One antenna at each receiving site has been extended to 1600 feet in length. This antenna acting as a signal-level antenna will be coupled to a comb filter of 160 sections, each 100 cycles wide. This narrow banding greatly increases the sensitivity for detection. When a tooth of the comb is activated, a local oscillator will be keyed on, which will tune the interferometer phase-measuring system to the doppler frequency of the received signal, thus causing this system also to function as narrow-band equipment. The overall result is the first step in mechanizing the system, and for this a 20-to-1 signal-to-noise ratio is set aside, but in addition there is about 12 db increase in sensitivity left to increase the range of the system. Also a measurement of the doppler shift is obtained which will be used in signal identification and processing, and further doppler sorting could be added to read signals arriving at the same time but not at the same position in the beam. This alert system is fully funded and will be installed throughout the line in 1961.

These two modifications serve to increase the range capability on a one-square-meter radar cross section object from about 450 statute miles to 2500 miles for a probability of detection of 95 percent. Triangulation coverage by at least two receiving stations will be provided over a line length of 3000 miles. Figure 11 illustrates the coverage now obtained with the experimental system and Fig. 12 shows the greatly improved coverage which will result from the funded program. This figure shows various contours of probability of detection. Figure 13 shows the distribution of earth satellites relative to maximum height. The improved system will observe most of them at apogee.

Another major area which is being improved is that of automatic operation (Fig. 14). Electronic devices perform a degree of filtering and classification of the signals at the receiver site. The signals are converted to digital form and transmitted over a telephone line to the digital receiver and buffer storage unit. Here the data are held for processing, as required, by the NORC computer. The computer not only processes the signal but also computes orbits, maintains a catalog of knowns, generates predictions and warnings, and converts the output information to the various forms required by customers of the system. It also supplies data in a form suitable for visual display, one type being represented in the figure. This display shows present satellite position on a world map, permits selection of any one or combination of satellites held in the computer store, and is capable of advancing or going back in time at high speed to show past or future positions and ground tracks. This automatic system is expected to be operational in December 1961. A more complete description of the digital computer requirements is contained in Appendix A.
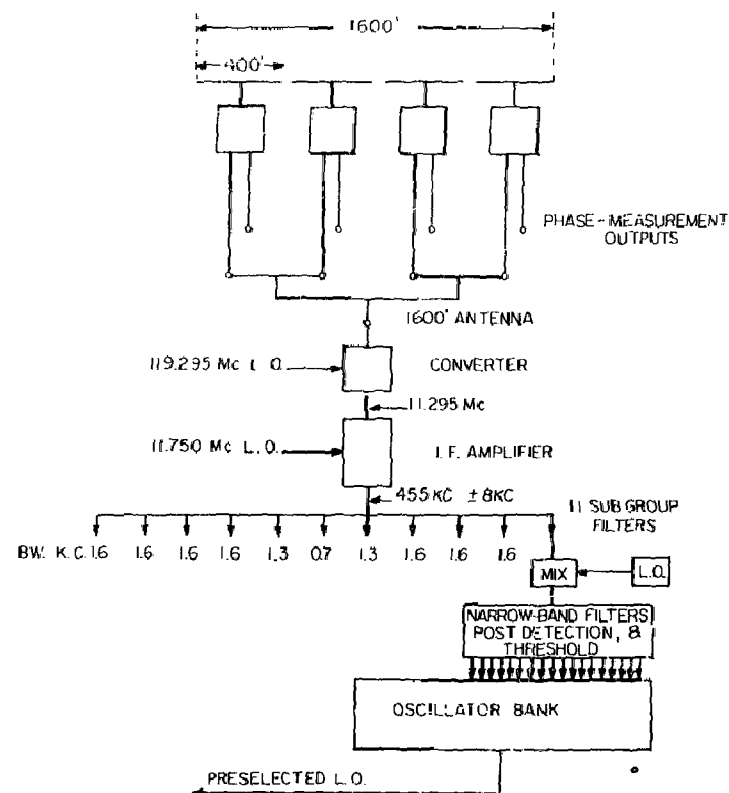
Fig. 10 - Method of increasing sensitivity
using an alert system
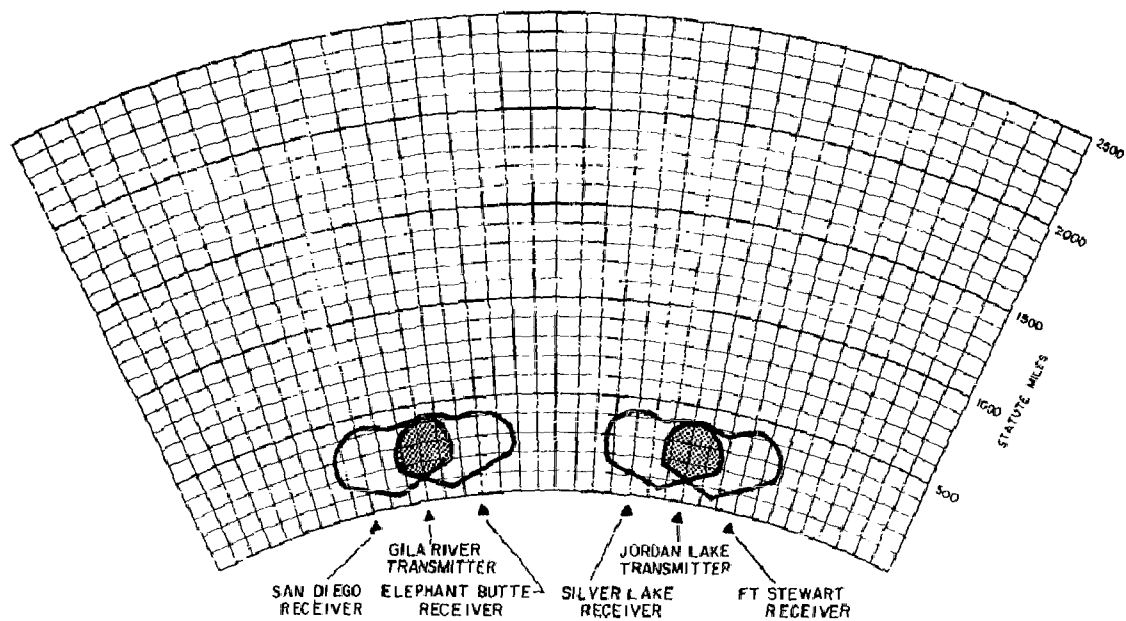
Fig. 11 - Coverage diagram for the system using 50-kw transmitters with
a 1600-foot antenna, and 400-foot receiving antennas, as will exist through
1960. The vertical lines represent 100-mile intervals on the earth's sur-
face.
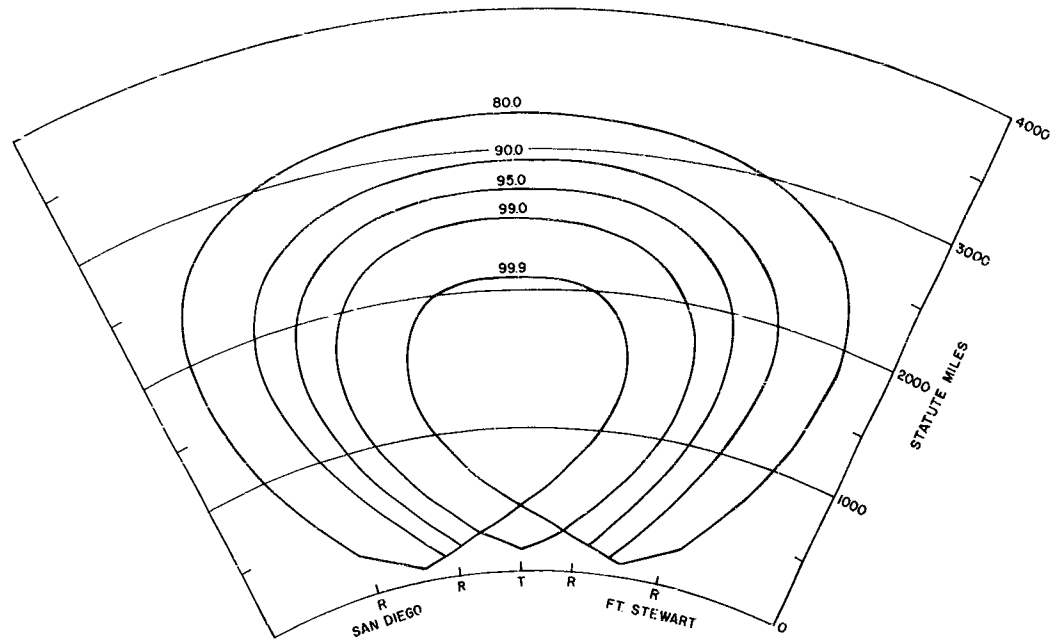
Fig. 12 - Observational probability vs coverage for funded developments
(radar cross section = 1 square meter)

Fig. 13 - Distribution of apogee
heights for satellites as of Sep-
tember 1960

RECEIVING   DIGITAL   OPERATIONS
STATIONS   DATA   CENTER
                 (TELEPHONE
                    LINE)

Fig. 14 – Block diagram of the fully automatic
Space Surveillance System

For a fully operational line, additional modifications are desirable. The most important is provision of good coverage at low heights. The minimum height of an orbiting satellite is about 100 statute miles having a period slightly less than one and a half hours. To insure that such objects are detected, the coverage at 100 miles should be continuous for a minimum distance corresponding to 22 degrees of earth rotation, or about 1500 miles. Because of interferometer baseline fores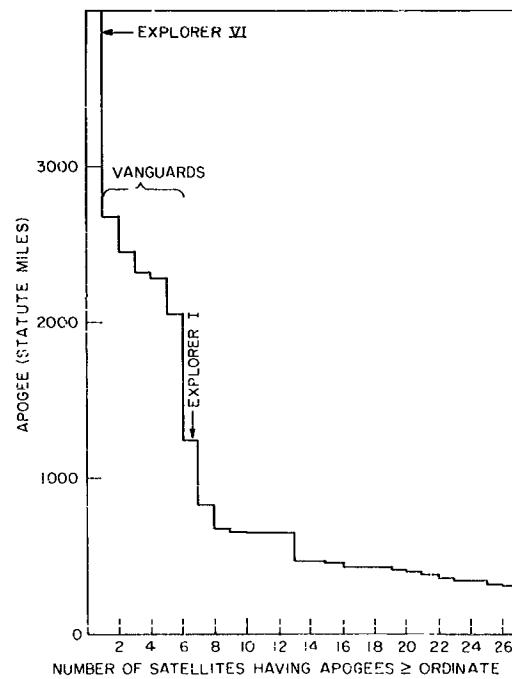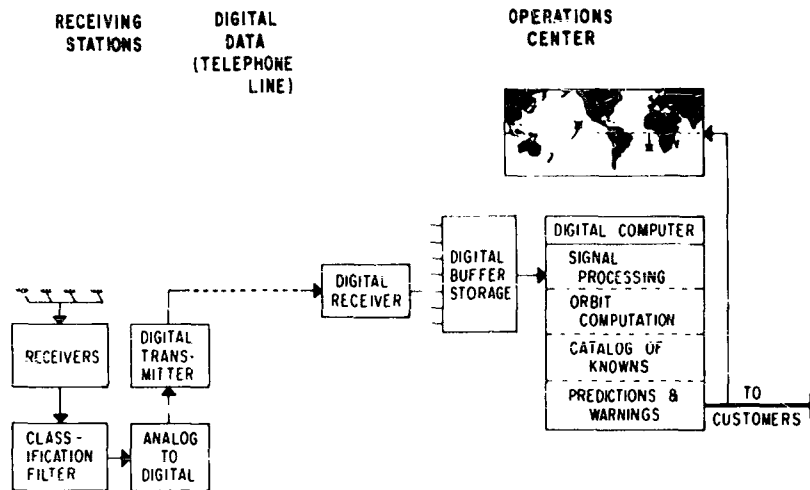hortening and refractive effects of the ionosphere, performance of the present line is not considered satisfactory for reception of signals beyond about 70 degrees from the zenith. Figure 12 shows that these low-angle criteria would not be met. It is recommended that small unattended secondary receiving stations be installed about 100 miles from the master receiving stations. Figure 15 shows the low height coverage that would be attained compared with that for the present four receivers. However, if these additional stations have the same capability as the master stations, the multiple receiver coverage would increase both the line length and the height coverage. Figure 16 compares the probability-of-detection contours of the funded program (broken lines) with that attained with the added receivers (solid lines).

If all receiving antennas were extended to a full 1600 feet as at Fort Stewart, the range of detection would be extended by about 40 percent.

Proposed Operational System

As originally proposed, a second surveillance line spaced so as to give measurements about two points well separated on the orbit is necessary for a quick-reaction orbit determination. This system would then have a capability of precise orbit computation fully adequate for predicting the next pass over the line and for giving look angles to any tracking devices that could be brought to bear on a newly detected satellite. Preliminary consideration has been given to the location of the second line. A line in the direction of Miami, Fla. to Fargo, N. Dak., has some attraction. In addition to the advantages of the two-line observations already discussed, the line spans a wide latitude so that successive observations would be well scattered about the satellite's orbit and it has the maximum N-S extent for
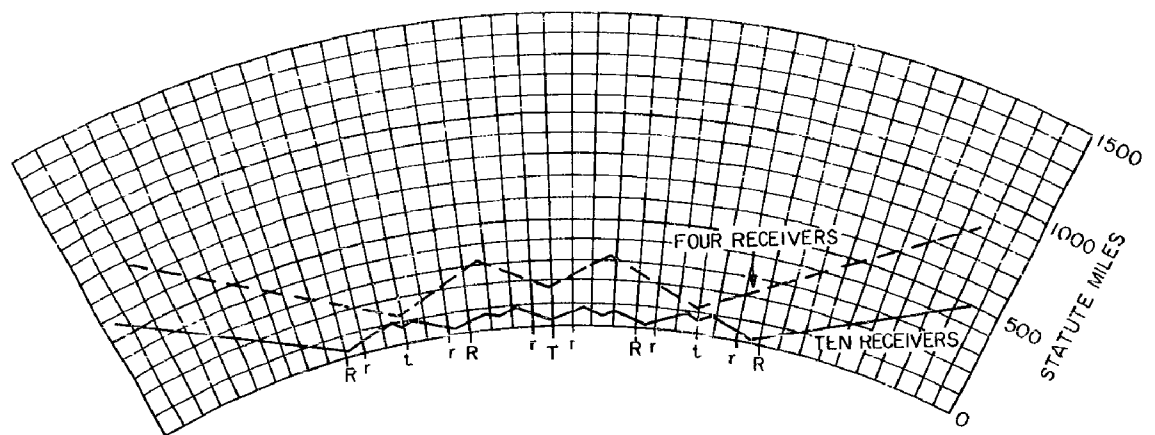
Fig. 15 - Improved low height coverage (solid line) with addition of secondary
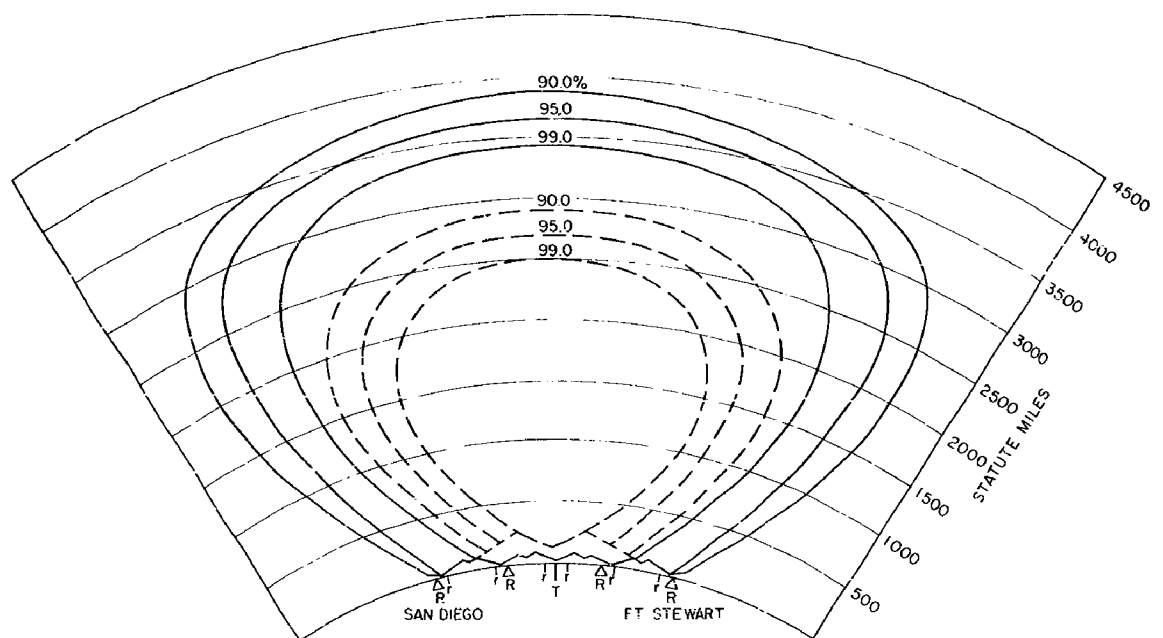receivers compared with existing coverage (broken line)

Fig. 16 - Increased coverage in heights and length if receivers were added
(solid lines) compared with funded system coverage (broken lines)

locations within the United States. However, if coverage of all inclinations down to equatorial orbits is required, an orientation somewhat more N-S to pass through the Canal Zone may be more desirable. A frequency of about 450 Mc is recommended. This frequency would provide an improvement over the present 108 Mc in that ionospheric refraction corrections would be reduced, the higher frequency would produce fewer reflections from meteor trails, and there would be less interference in the northern latitudes from auroras. Using two frequencies in the system would substantially increase an enemy's difficulties in obscuring his satellites with radar absorbent materials.

SYSTEM EVALUATION

Jamming and Interference

This system, being an angle-measuring system, cannot be jammed in the same way as a pulse-range-measuring radar. A weapon-borne jammer merely aids the system in angle measurement by providing its own good signal. The interference problems to be contended with are feedthrough from transmitter to the receivers and noise from the sun and radio stars.

Feedthrough was experienced in the experimental system when the transmitter and receiver used dipole antenna elements with the electric vectors parallel. With the polarization crossed, feedthrough is greatly reduced. Because the ionosphere rotates the polarization vector (Faraday effect) as signals pass through it, there is no advantage in transmitter and receiver polarization being parallel. If only linear polarization is used some signals will be missed. This will have the effect of reducing the system range, or alternatively of increasing the required cross section for a useable signal. However, since range enters as the fourth power in comparison to the first power of the cross section, the coverage loss is not too great. It is intended to evaluate use of circular polarization on the new central transmitter antenna but this in itself would cause a 3-db loss in power when using linear polarization for reception. The alert system uses doppler filters so feedthrough can be eliminated by a rejection filter at the transmitter frequency with very small chance of loss of a satellite signal.

At times when the sun intercepts the receiving beam, noise is introduced in the system which can prevent reception of the satellite reflected signals. This is most serious at times of high solar activity. Outages from this cause appear to average less than 1 percent of the time. This type of interference will be reduced by the narrow-band alert system.

Traffic Capacity and Resolution

The traffic capacity is large. The minimum satellite period is about 90 minutes and many satellites will be in higher orbits with greater periods. Successive orbits would then be spaced 22-1/2 degrees or more in longitude over the earth's surface. Each receiver would see a given satellite about twice (front and back side of the orbit) each 24 hours, or twice in 86,400 seconds. It is obvious that a large number of satellites could be accommodated without mutual interference except for a very low percentage of the time. When bunching does occur, sorting of simultaneous signals by doppler-frequency difference is possible with the alert system. Angle measurement may be made on either a time shared basis or with multiple electronic phase meters. Thus the system has the capability of handling large numbers of satellites, in the tens of thousands, as constructed, with expansion to millions through use of individual phase meters on narrow doppler channels. Further, consideration has been given to multilobe receiving beams to provide increased gain and simplify the interferometer. This would provide even greater traffic-handling capacity.

Satellite Observations

It is the purpose of the feasibility program to evaluate the technique of using cw radar with a high-precision interferometer for satellite detection and tracking. The detection capability of this technique has now been confirmed.

Figure 17 illustrates the theoretical coverage of the experimental system as it now exists. It uses a 50-kw cw transmitter operating at 108 Mc coupled to a 1600-foot transmitting antenna (30 db) and receivers using only 400-foot antennas (24 db), except at Fort Stewart where 1600-foot antennas have recently been installed. The coverage diagram is referred to a satellite reflecting area of one square meter giving height coverage up to about 450 statute miles. The overlap area, very limited in this experiment, restricts the number of passes where triangulation can be obtained. During April 1959, the third stage rocket (1959 Alpha 2) which placed Vanguard II in orbit passed low over the line and moved through the coverage pattern in a synchronous manner. Figure 18 is a plot of the observations on this satellite superimposed on an outline of the theoretical coverage limit as of the Spring of 1959. This rocket casing, 18 inches in diameter and about 5 feet long, has a radar cross section of 0.2 to 2 square meters. The first observation was made by Fort
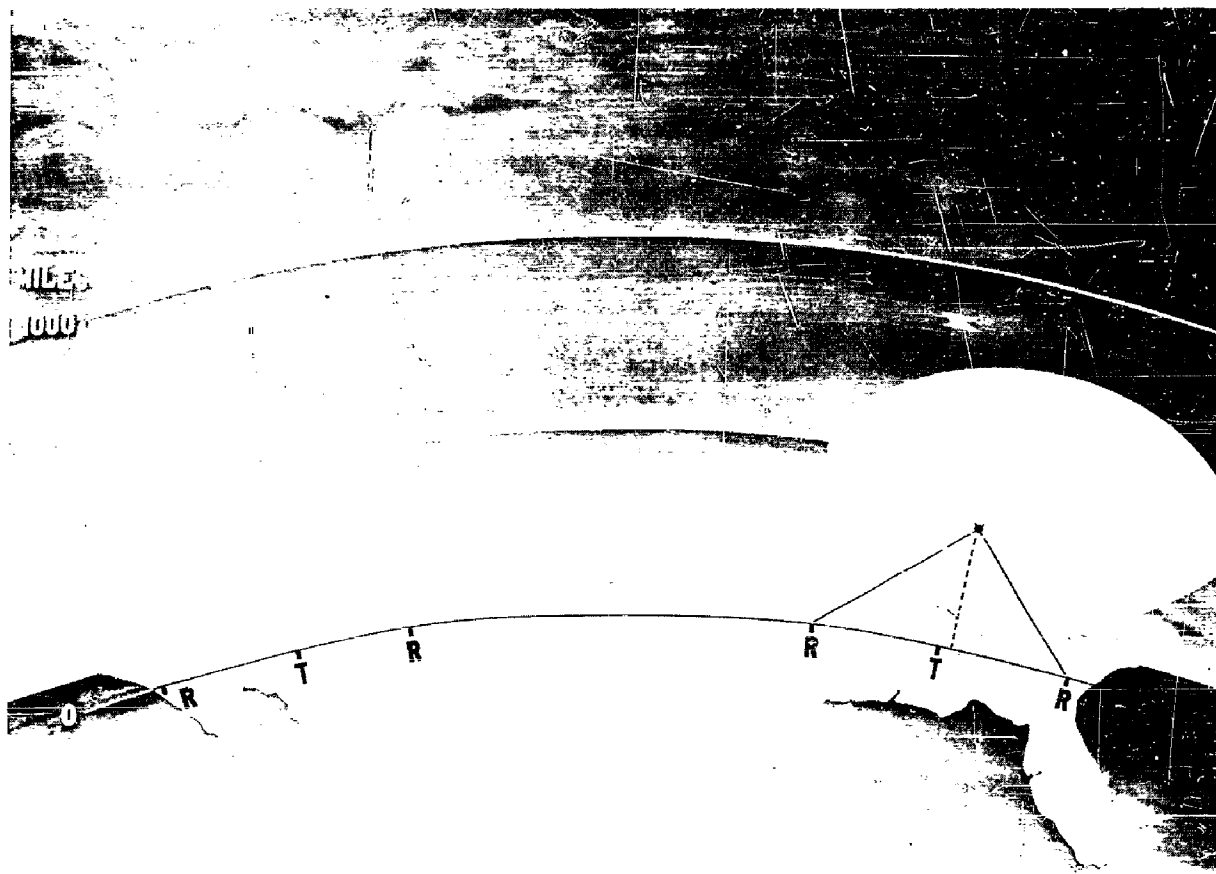

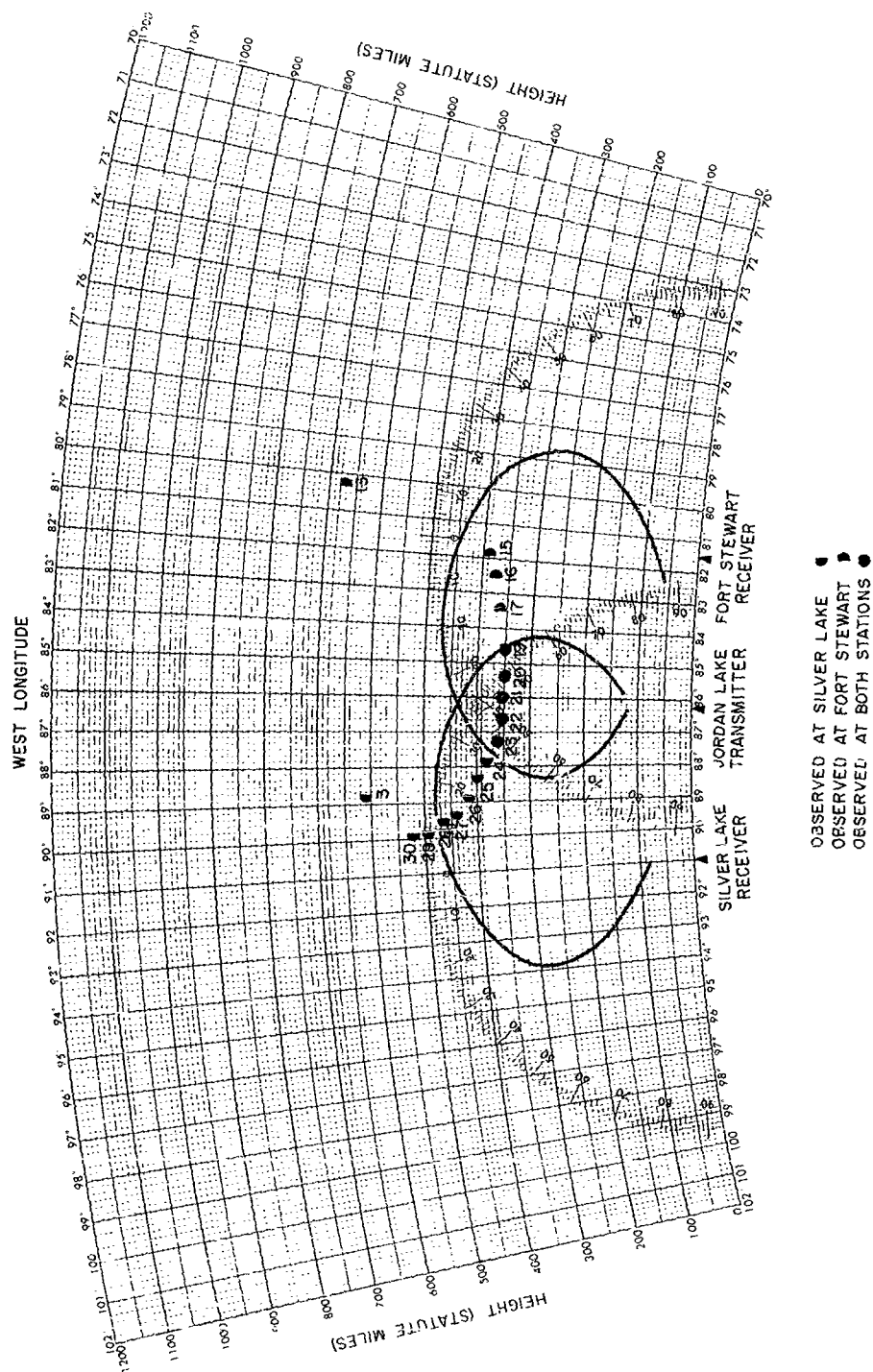Fig. 17 - Coverage of the SPASUR experimental system for a one-square-meter radar cross section

Fig. 18 - Space surveillance vertical plot for the Satellite 1959 Alpha 2 (a theoretical coverage diagram for a one-square-meter target is superimposed). Observations from April 13 to May 3.

Stewart on April 13 and it was seen again on the 15th, 16th, and 17th; on the 18th, the transmitter was down and then it was seen each day from the 19th through the 30th. The full circles denote observations by both receiving stations. The half circles, representing single station observations, were plotted at the intersection of the measured angle of arrival with the known orbital plane.

Figure 19 is a plot of all passes of Discoverer VIII (1959 Lambda) during its life, in the vicinity of San Diego. Open circles denote predicted passes that were missed by this station while solid dots indicate reception. Observations are grouped over the receiver and toward the transmitter as would be expected. Cross-section calculations for these observations indicate values from 0.1 to 25 square meters with a median of about 2 square meters. The majority of missed passes lie outside the expected coverage though some lie within. These are accounted for by tumbling which presents a variable aspect to the system and by the polarization effect. The experimental installation uses linear polarization. Because of the rotation of the polarization by the Faraday effect as the signal passes through the ionosphere, the polarization at the receiver is random. The measured cross sections are influenced by both aspect and polarization effects. Receiving antennas on both polarizations have been installed at Fort Stewart and are being used to make a statistical evaluation of these polarization effects. A determination will be made as to whether it is more advantageous to provide a dual polarization system or increase the system sensitivity to overcome the reduction in signals.
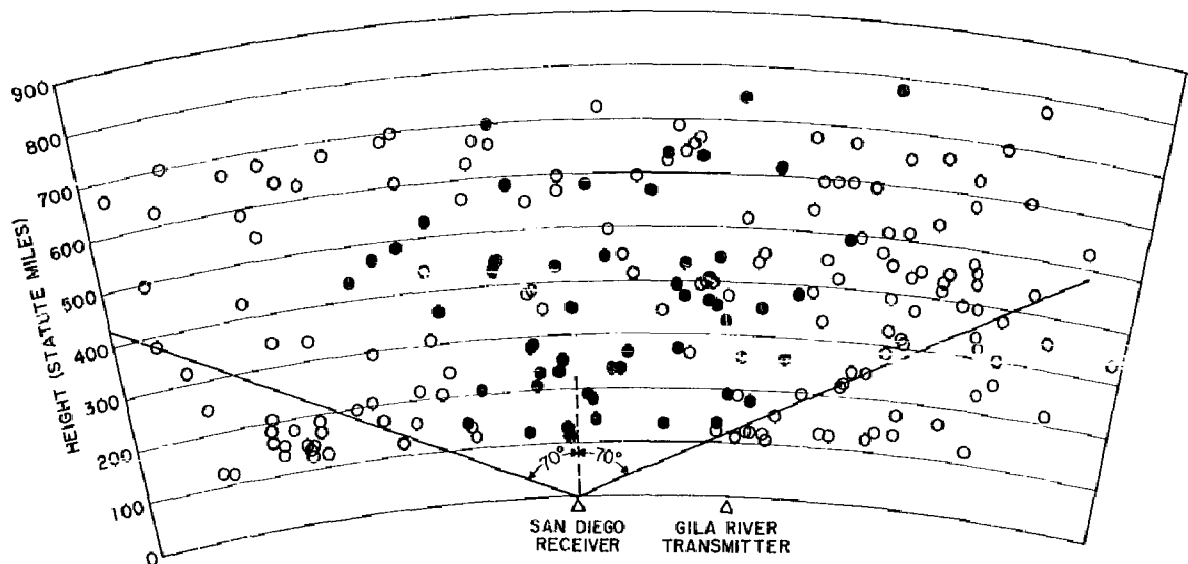
Fig. 19 - Plot of all passes of Discoverer VIII (1959 Lambda) in the vicinity of San Diego. Dots represent San Diego observations, circles represent predicted passes not observed at San Diego.

Table 1 lists the number of observations made by the system for each month since the Operations Center was established. The number of different satellites observed is also shown and may be compared with those in orbit at the end of the month. Because of limited coverage, some (Lunik III and its rocket) are never observed. Others are seen only when perigee is over the line (Vanguards) and many are missed because the passes occur to the side of the short sections of line coverage in each Complex. Evaluation of these observations indicates there are no unanticipated problems in the sensitivity or coverage area. Extrapolation of the coverage for the higher powers and increased receiving gain proposed for the improved system appears to be sound.

Table 1
SPASUR System Satellite Observations

Month	No. Satellites in Orbit* (end of month)	No. of Obs. by SPASUR System**	No. Satellites Obs. During Month
July 59	7	170	5
Aug. 59	10	217	6
Sept. 59	10	462	8
Oct. 59	12	213	5
Nov. 59	13	368	7
Dec. 59	12	263	6
Jan. 60	14	360	8
Feb. 60	15	438	8
Mar. 60	16	350	7
Apr. 60	19	314	11
May 60	28	449	16
June 60	31	785	19
July 60	30	854	11
Aug. 60	30	1279	17
Sept. 60	29	1931	20

  * Includes Lunik III and final stage and large
     fragments of other satellites known to be
     in orbit.
** Includes only current observations produced
     by routine operation.

Measurement Precision

Another area of evaluation deals with the measurement errors and the precision with which orbits may be computed and predicted. The volume in space representing the uncertainty in determining satellite position varies with the zenith angle of the observation because of baseline foreshortening and the ionospheric refraction correction which places a limit on the angle measuring system. The limit now is really one of lack of knowledge about the ionosphere and how it varies. With the 108-Mc frequency used in this experiment, the refractive correction amounts to a fraction of a degree at large zenith angles. Figure 20 illustrates the magnitude of the correction and how it varies at this frequency. For 450 Mc, which is recommended for a new line, it is estimated that this error can be corrected to better than 10 seconds of arc. Another factor in accuracy of measurement is related to the length of the interferometer baseline. For maximum accuracy, the baseline should be extended so that it will not be the principal source of error. The area in space representing the uncertainty in measurement is illustrated in Fig. 21, when using baselines of 500 wavelengths.

For highly precise orbits in a single pass, the complete two-line system is required. This gives two precise position fixes about two well separated points of the orbit. Table 2 relates the angular measurement error to the error in computed orbit in terms of error in position prediction for the next pass.

A PUERTO RICO; 0800, 25 FEB 59; 250 km
B PUERTO RICO; 0800, 25 FEB 59; 500 km
C WHITE SANDS, N MEX.; 1400, APR 59; 250km
D WHITE SANDS, N MEX.; 1400, APR 59; 500km
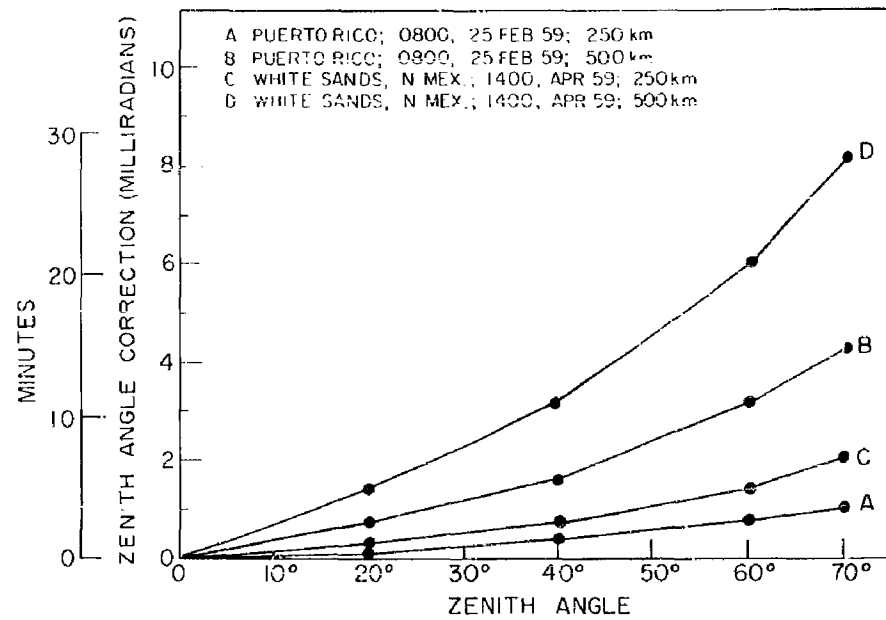
Fig. 20 - Refractive correction vs observed zenith angle

MEASUREMENT ERRROR
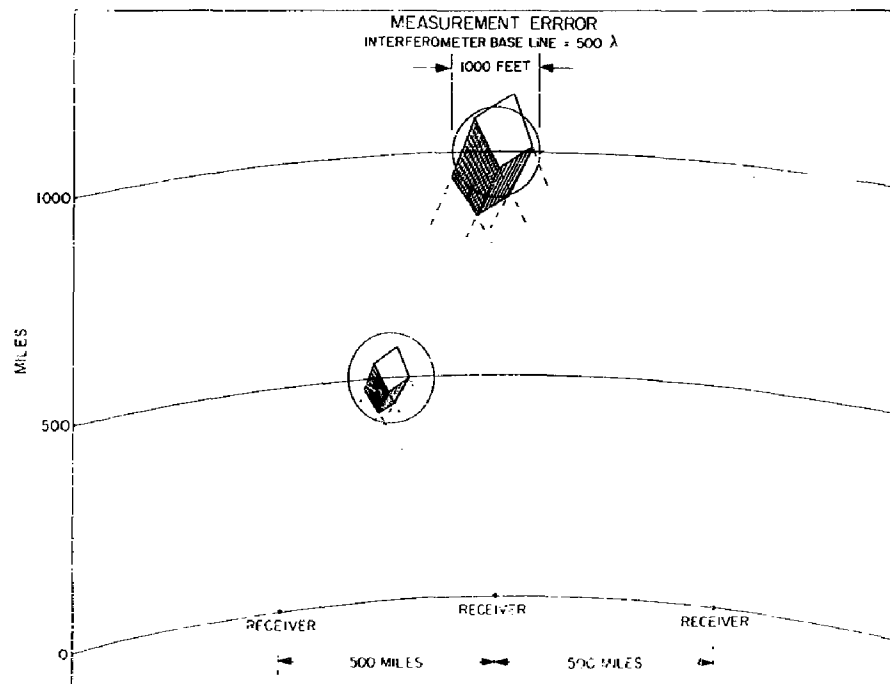INTERFEROMETER BASE LINE = 500 λ
1000 FEET

Fig. 21 - Accuracy of position determination using
interferometer techniques

Table 2
Prediction Error for Two Lines, Single Pass

Line Separation (statute miles)	Observation Height (statute miles)	Prediction Error of Next Pass*	
		Zenith Angle (mils)	Time Over Line (Seconds)
100	200	10	8
	2000	4	28
500	200	2	2
	2000	1	6
1000	200	1	1
	2000	0.5	3

*For observations made midway between transmitter and receiver.
Errors may be larger, up to double, for observations at large
zenith angles.

Calibration

The accuracy of measurement depends upon adequate calibration. The electrical measuring system must be oriented to zenith angles. Because of the large antenna length and long baselines used in the receiving system, aircraft-carried calibration equipment is precluded. To date the antennas have been positioned using surveying and electrically measured transmission lines and have been checked using known positions of satellites, indicating the method is good to ±0.5 degree.

It is possible to improve the accuracy to ±0.1 degree by using optical methods. Both the ballistic camera and cinetheodolite are being explored for this purpose to establish satellite positions relative to the star background. The variations of the ionospheric refraction (Fig. 20) limit any long term calibration. For the system to operate essentially in real time, these variations must be determined on a continuing basis with small delay. It is estimated that an accuracy of ±0.01 degree can be achieved in an operational system at the existing frequency of 108 Mc. The method involves using a number of satellites carrying a transmitter on some frequency such as 1000 Mc which is essentially unaffected by the ionosphere. The satellite position is determined precisely by optical methods through observations at twilight, which will be used to calibrate a separate high-frequency interferometer (limited baselines required). A comparison can then be made between the reflected signal at 108 Mc and the transmitted signal at 1000 Mc each time one of these satellites crosses the line. This method provides immediate calibration for ionospheric refraction at frequent intervals as neither photographic plates nor reduction of photo data need be made.

Orbit Computation

Although the experimental system provides only single line detection and has only limited baseline resolution, reasonably good orbits can nevertheless be computed.

If observations can be made on opposite sides of the orbit, and one is willing to wait about 12 hours for the earth to rotate through these positions, a more precise orbit can be computed. To illustrate, observations were made on a radiating satellite, the NRL

Solar Radiation Satellite (1960 Eta 2). It was also observed by the NASA north-south passive Minitrack fence, thus providing a reference orbit using a completely independent system. Orbital parameters were computed and compared with the NASA orbital parameters. The NASA orbit was based upon one week of observations made at stations located at various latitudes and thus observing the satellite at widely different points in its orbit. A minimum number of observations were used for the space surveillance system computation, consisting of one triangulation in a N-S pass and one in a S-N pass (opposite sides of the orbit), and one additional single-station observation to give a good initial determination of the period. The variation from the NASA orbit and the consistency of SPASUR elements are illustrated in Table 3. This table demonstrates the limiting orbital parameter capability of the improved single line, computations being based solely on data collected from newly detected objects over approximately 12-hour periods. For satellites of the size now being launched in relatively low orbits this limit should be closely approached.

The elements can be improved as observations are accumulated. Since the fence is located at essentially one latitude and can therefore only observe two points on the orbit (without waiting a long time for perigee to move around), it is of interest to determine whether this may be a limitation on precision. It has been standard operating practice to make line crossing predictions in advance for all satellites, using the orbital elements derived from past observations. The deviation of observations from predictions may be used to assess the accuracy of the original elements. At the level of the present state of the art, it appears that there is no disadvantage in using only SPASUR observations when there is an adequate number. At the present time variable atmospheric drag affects orbits so that predictions of time of crossing of many current satellites are in error by one minute in a week. At times when drag is more constant, the predictions may be much better. As an example, Fig. 22 is a plot of time differences between line crossings and predictions for Sputnik IV Fragment (1960 Epsilon 3) where the difference remained less than 10 seconds for 3 weeks in advance, until a change in atmospheric drag disturbed the orbit. Unless these atmospheric changes can be predicted, long term orbit prediction for low satellites will remain inaccurate.

SPECIAL INTEREST SITUATIONS

The primary purpose of this system is to detect unannounced, nonradiating satellites. To exercise the system on unknowns presents some difficulties; however separations or breakup of orbiting bodies have provided this opportunity. The first was the detection of the rocket body for Explorer VII, which was picked up by the system and identified shortly thereafter. A second unknown was later determined to be the re-entry body of Discoverer V (1959 Epsilon 2). This particular satellite was first determined to be in orbit on February 2, 1960, whereas the parent satellite was launched August 13, 1959. It now appears that this body was given an increase in energy rather than a decrease as intended to return it to earth. Because of the small size of this object and the limited capability of the experimental SPASUR system, it was with considerable difficulty that observations were traced back through the records to the time of attempted separation. No observation could be found earlier than this time.

The attempted modification of the orbit of Sputnik IV (1960 Epsilon 1) resulted in energy being added and a separation into several fragments. Figure 23 shows sections of the Sanborn recordings of a pass of these fragments through the fence where seven were observed in addition to Epsilon 2, the rocket body. Epsilon 3 exhibits a rather stable orbit indicating a degree of symmetry and low drag. The task of keeping track of these objects is illustrated by Fig. 24 which plots the difference in time of line crossing relative to Epsilon 3 for several succeeding days. Initially the miscellaneous objects trailed Epsilon 3, indicating they had energy added to place them in slightly higher orbits. However,

Table 3

Comparison of Orbital Elements for the Satellite 1960 Eta 2 Derived from a Minimum of
Space Surveillance Data with NASA Minitrack Elements Used as a Reference

Space Surveillance Elements Minus NASA Elements

Elements* Derived from	Anomalistic Period† (min)	Inclination (deg)	Eccentricity	Argument of Perigee (deg)	Right Ascension of Ascending Node (deg)	Mean Anomaly at Epoch (deg)	Perigee Height (statute miles)	Apogee Height (statute miles)	Semi-Major Axis (statute miles)
NASA	101.64526	66.769	0.03070	232.720	105.325	234.811	382.1	657.4	4,483.1
Revolution									
1 & 10	-0.00026	0.023	-0.00050	-2.39	-0.025	1.70	2.2	-2.3	0.0
15 & 24	-0.00026	-0.013	-0.00100	-6.37	-0.055	5.95	6.2	-6.3	0.0
66 & 71	0.00074	-0.190	-0.00071	-3.12	-0.065	3.56	3.2	-3.2	0.0
85 & 94	-0.00016	-0.195	-0.00045	-4.46	0.015	0.55	2.0	-2.1	0.0
127 & 136	0.00044	-0.154	0.00008	0.51	0.055	-7.57	-0.3	0.3	0.0

*The elements for each set of revolutions have been adjusted to the epoch of the reference elements, namely 1960 June 22/0620002. To illustrate variation of computed values period was
†Period can be determined to ±0.002 minutes using consecutive revolutions.
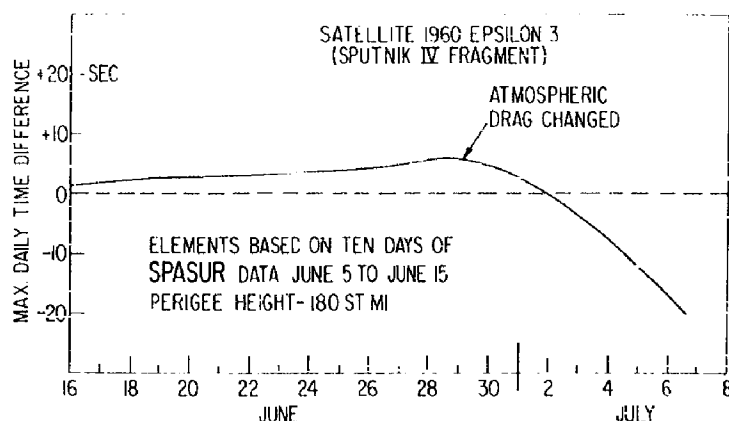determined from data 14 revolutions apart.

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Fig. 22 - Comparison of line crossing predictions
with 66 observations

after about 5 days the drag effect shows up as these objects begin to overtake and finally pass number 3 as they go into lower orbits.

GROWTH POTENTIAL

Since this project has provided the only capability this Country has for the detection of nonradiating satellites, there has been pressure to use whatever capability could be obtained to fill an immediate operational gap. Manual data reduction methods have been employed while automatic methods are being developed. A demonstration of transmission of digital data from one receiving station to a buffer store at the computer site will be conducted early in 1961. Completion of the digital system is scheduled for the end of 1961 at which time automatic operation will have been introduced throughout the system.

The approved program greatly increases the detection altitude, rising from a height of 450 to about 2500 statute miles on one-square-meter objects. Receiving antennas may be extended to 1600 feet (ground screens are installed) which would extend the height coverage to about 3500 miles. Higher-gain alert antennas should accompany the extension of the phase antennas. A multilobe alert-antenna design is recommended to maintain the signal duration. Power may be increased simply by adding to the existing transmitter. The present output stages may be used as drivers for larger final amplifiers. Very-high-gain phased arrays may be used to further increase the range. The post-detection bandwidth may be decreased for larger ranges to better match the signal duration. The present system provides baselines of only 521 feet, except for Fort Stewart. Longer baselines may be provided simply by adding antennas and phase meter electronics. These longer baselines are required as greater precision in orbit computation becomes necessary, and particularly as precision is required from a small amount of data. At present good orbital parameters are obtained after a series of observations. However, the operational system will require good orbital predictions as soon as possible after a new object is detected.

The above growth features enumerate items which can be accomplished one at a time as funds become available. The system design is such that they may be had merely by adding to or modifying existing installations without serious interruption of operations and without obsoleting expensive equipment.
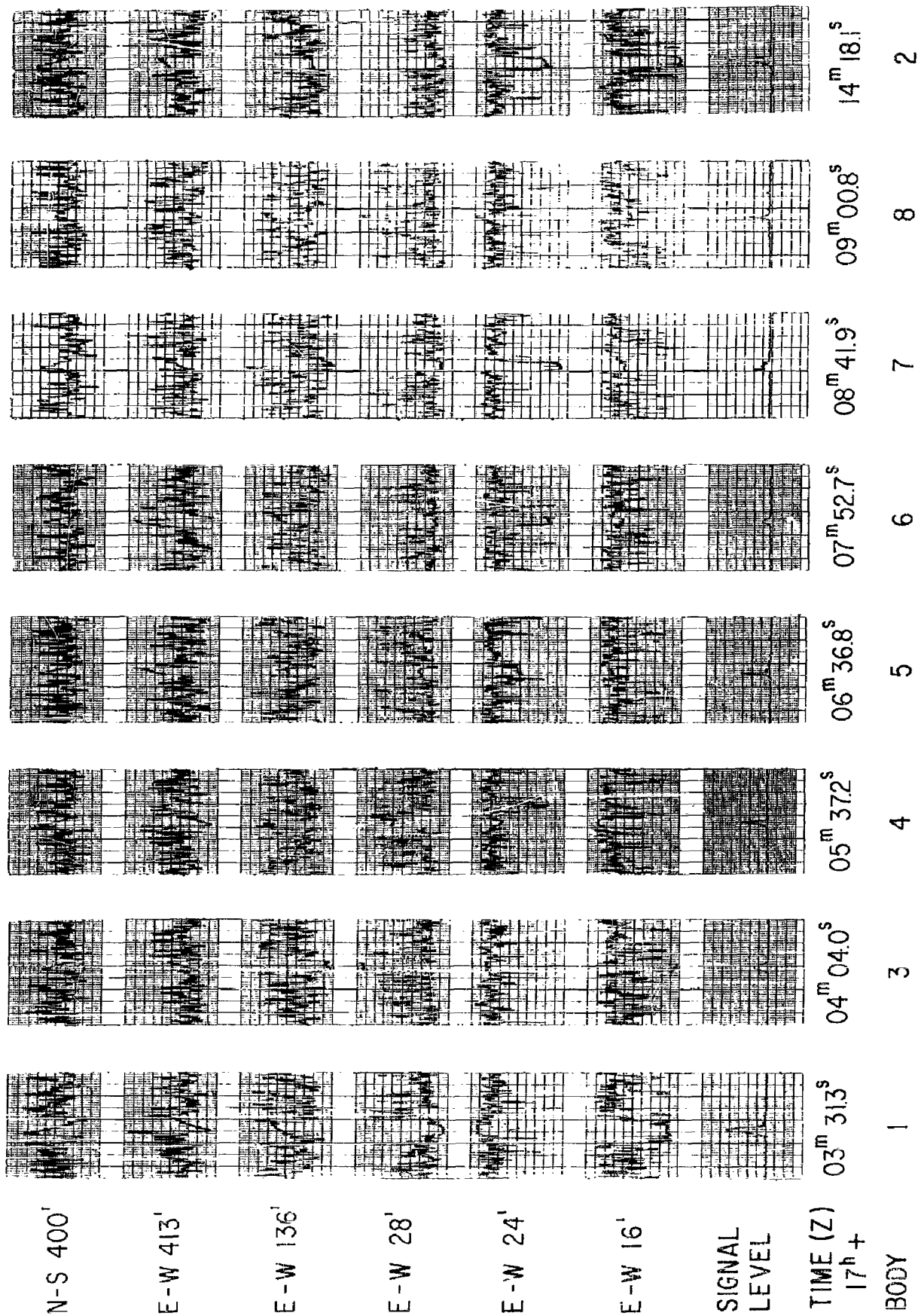
Fig. 23 - Observations of 1960 Epsilon 1-8 (Sputnik IV) at Fort Stewart on 20 May 1960
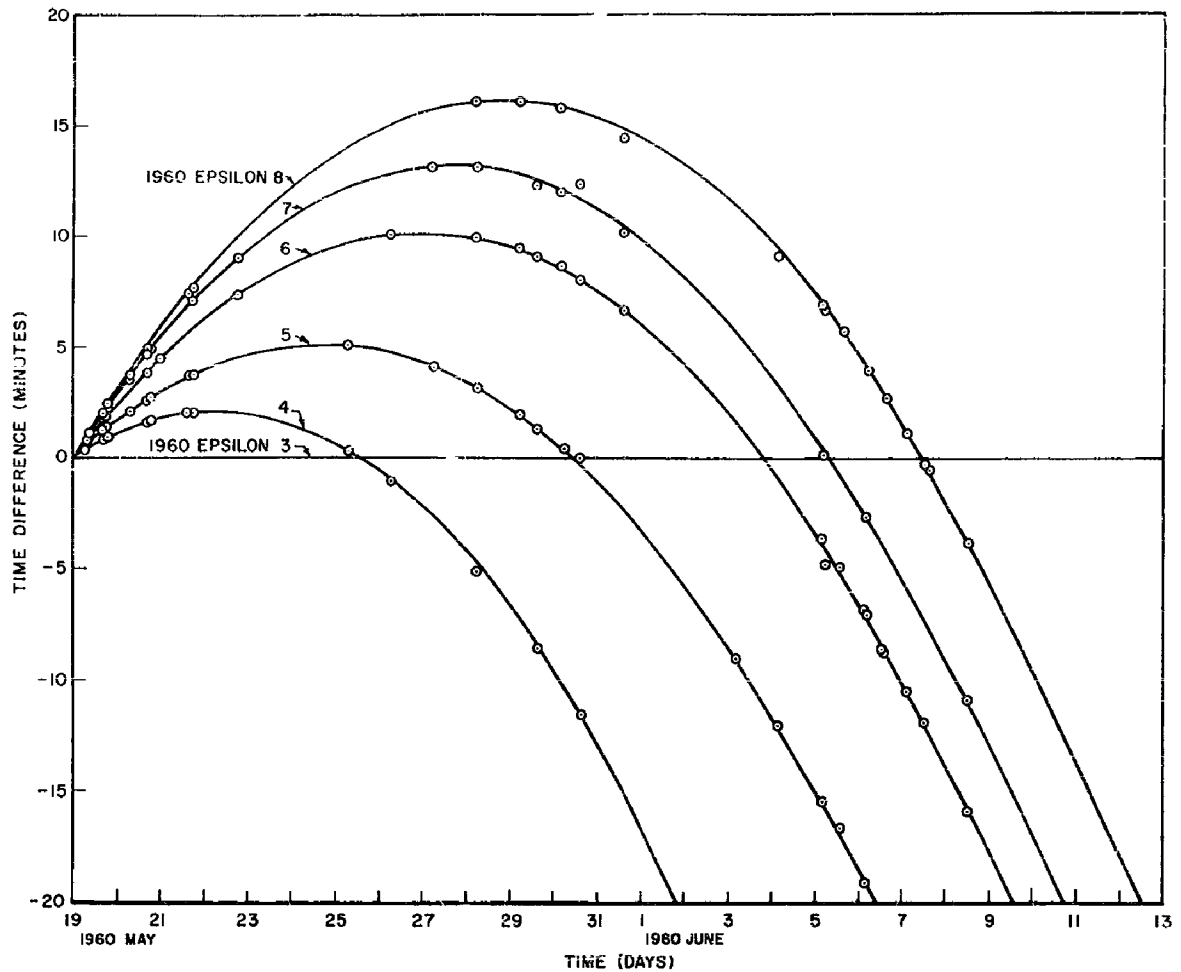
Fig. 24 - Time difference in observation of Epsilon fragments with respect to
the passage of 1960 Epsilon 3 through the Space Surveillance Beam

If operational requirements exist for a greatly increased capability, the techniques
being developed in this program can be applied to such expansion. For example, ability
to detect orbits of all inclinations may be desired. A fence oriented in a north-south
direction extending to the equator would be indicated. If greater ranges are required,
this may be accomplished also. Figure 25 illustrates a possible north-south line located
to take maximum advantage of continental United States locations and existing communi-
cation facilities. The high-detection portion would be based between the northern and
southern borders of the Country, giving two-station triangulation coverage over the equator
in a sector extending upward for several earth diameters. The transmitter would radiate
2 megawatts at 450 megacycles. Antennas would be about 800 wavelengths long. Tapered
comb-filter bandwidths to 10 cps and post-detection bandwidth of 0.1 cps are assumed for
maximum ranges. An additional receiver in the Canal Zone would fill in coverage over
the equator down to less than 2000 miles in height. To provide low height coverage over
the equator would require the addition of a small transmitter near Quito, Ecuador, and a
receiver at perhaps Lima, Peru. These locations are suggested since the United States
has facilities at these locations; the major data flow would be confined to the continental
United States, with good communications in the Canal Zone and only limited requirements
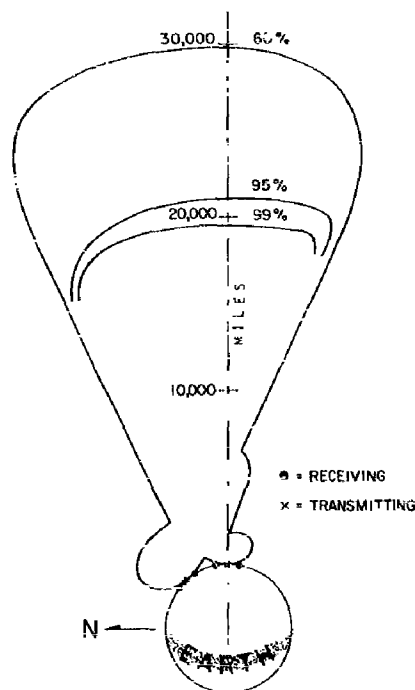for data from South America.

Fig. 25 - Coverage attained in a possible line designed for long ranges and including equatorial orbits

SUMMARY

The system which has been described is simple; it has no massive components or rotating machinery. It is an angle-measuring system and thereby has anti-jam advantages since a weapon-borne jammer merely aids the measurement. There are no artificial limitations on maximum range since only angular measurements are required. The system is flexible and has adequate future growth potential; its range capability may be extended to meet additional short term requirements. This can be accomplished through increased transmitter power and antenna gains. The large transmitters are formed by adding power amplifier units in a phased array rather than by changing the unit design. Antennas may be increased in size by extending existing installations. Additional interferometer baselines may be added to increase the precision of measurement. The system can handle large numbers of satellites through use of (a) short observation periods thus employing time separation and (b) doppler sorting. Measurement accuracy is limited by our knowledge of the refractive effects of the ionosphere which is in turn a function of frequency and zenith angle. It is recommended that a transmitter frequency of 450 Mc functioning through baselines 500 wavelengths long be employed. These design parameters will yield range errors of less than 1000 feet at satellite distances of 1000 miles and will lead to the ability to predict within about a second the time of the next pass of a satellite from data collected from a single pass across two detection lines spaced 1000 miles apart.

Phase I of the system has been completed. It provides a feasibility demonstration and has supplied an operational capability up to 450 miles on a one-square-meter target over a short length of line.

Construction of a 500-kw cen·al transmitter, addition of the alert system, and making the system completely automatic are all in process and when completed during calendar 1961 will greatly increase the operational capability. But provisions for gap filling down to 100-mile heights and extended baselines for more precise measurements, though desirable, are not funded for installation at this time.

A second line in an approximate north-south direction is recommended for the operational system. Such a line extending approximately 4000 miles on the surface and monitoring up to 3000 miles in height would cost approximately 20 million dollars. The system could be extended both to greater heights and greater extent, including equatorial orbits, as operational requirements become more severe.

The data reduction, operation, and orbit computation responsibility as well as the development of the automatic digital data processing system were assigned to the Operational Research Branch headed by Mr. J. J. Fleming.

These two Branches have carried the major effort in producing the system and operating it to date; however, they have been assisted by personnel from the Data Processing, Engineering Psychology, and Systems Analysis Branches of the Applications Research Division.

* * *

APPENDIX A

DIGITAL COMPUTER REQUIREMENTS IN THE SPACE SURVEILLANCE SYSTEM

It is visualized that any system satisfactory for military operational use must provide output data with a minimum of delay. This continuous type of operation is often spoken of as "real time" operation, and a computer operation which accepts data directly from the sensor devices is termed "on line" operation. These conditions will be approached in the automatic system. However, there will be a buffer store to hold data while the computer is busy completing a calculation, and the system output, which is orbital elements, will be delayed to the extent necessary to combine and reduce the data. Orbital elements is the form of output which uniquely describes a satellite and provides the identifying basis for determining when something new is in orbit.

The signals appearing at any one receiving station represent only part of the input into the computer. Signals from at least two receiving stations must be combined to produce an observation; and to realize the maximum probability of detection, all received signals must be combined. This requires bringing all receiver station outputs to a central processing point. This will be done by a digital transmission system which samples the receiver output at about 20 times a second. In fact, the receivers have many outputs which are simultaneously sampled. These samples record the difference in electrical phase between each pair of receiving antennas, the amplitude of the signal vs time, the frequency of the signal (which varies from the fixed frequency of the transmitter by a doppler shift dependent upon how the satellite moves with respect to the transmitter and receiver), and information derived locally relative to the signal shape.

The incoming signals from the receiver sites are meaningless until combined with other information and processed. First, calibration data must be inserted. This is in two forms: that characteristic of the fixed geometry of the system -- station location, antenna separations, nominal cable lengths, etc., - and that which varies with time -- voltages and ionosphere characteristics. The multiple signals are combined to produce positional information relative to an observation. Direction cosines for individual sites are computed, then combined from different sites to derive three-positional coordinates. However, before arriving at this point several computational checks must be performed to avoid large numbers of false observations. Time correspondence between signals from different stations must be examined. To a first approximation the signals must be simultaneous. However, this is not strictly true as the time correspondence depends on where the satellite crosses the line and on propagation effects. These checks are made within rules set up in the machine. If this check is met, a tentative height is computed provided the direction cosines converge, thus giving a tentative position in space. Now the validity of each receiver signal is assessed by requiring that (a) the observed doppler frequency shift agree with that computed for the position of crossing the line and (b) the computed position must agree with those additional signal characteristics related to the orbital elements which can be estimated. These factors include the angle of crossing which may be computed from the phase data, the phase rate which relates to the velocity of the satellite, and the height indicated on the basis of a valid triangulation. Having established an observation, it must either be associated with a known satellite by having been made at the time and place predicted within certain "gate" tolerances, or be classed as other. Upon the receipt of the first full observation (triangulation), not eliminated by association with a known orbit, a sorting process is initiated to associate any

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previous single-station signals which are satellite type with this observation to produce a consistent set of orbital elements. These single-station signals will include many non-satellite signals held in storage for possible future use. By arranging in sets having consistent features, orbital elements may be produced. Again after tentative selection, the validity has to be established through compatible doppler.

Thus the system is a closed loop arrangement which must first perform a calculation to produce tentative observations which then have to be checked against other signal characteristics for compatibility as a means of eliminating false alarms. These characteristics are related on the basis of a specific orbit on which the observation is made at a specific point. This orbit is described in terms of orbital elements, six being required. This process of accepting partial signals, combining them to obtain positional information, comparing and sorting, and finally validating the tentative observations can only be accomplished by machine methods when the satellite population reaches a magnitude not too much greater than now exists. Further, this processing must be continual and rapid and must accept nonsatellite signals, eliminating them as the processing proceeds. Therefore, for this procedure to move smoothly and rapidly, the "on-line" use of a computer becomes a necessity.

While there are various characteristics which such a computer must have, two are significant and are easily visualized. One is a large storage capacity. This is obvious from the large amount of data the system must process. The other relates to accuracy of calculation. Most of the observations will cover known objects, but each observation must be definitely identified in order to find any possible unknowns. This task will be the major processing task and the system design must give strict attention to reducing the routine work in this area. The ease and certainty with which an observation can be identified with a known is dependent upon the narrowness of the "gate" limits which may be established as to when and where each known satellite should be observed. Now one might make this calculation each time a satellite were observed, for its next expected pass – a tremendous amount of calculating. Obviously one wants to make accurate calculations, far in advance, satellite by satellite, placing the results in storage until needed. How far in the future, however, is dependent upon the accuracy which can be attained. This accuracy is dependent upon the accuracy of observations, knowledge of satellite behavior (prediction program), and the capability of the computing system. These should be in balance.

In addition to the direct processing of data described above, the computer will provide the "brains" to oversee and monitor the complete system. It will continually perform checks and advise supervisory personnel of performance status. The receiving stations' performance will be checked. Each interferometer baseline will come under observation individually at certain phases of the data reduction process. Faults which may arise will immediately be announced through display alarms. The sensitivity of the various baselines will be continuously compared so that deterioration in any one will be found early.

Some faulty operations will be acted upon automatically. For example, garble in the data transmission, disclosed by error code check, will be automatically eliminated. On a broader basis, the entire system will be monitored through a "Figure of Merit" display which will indicate the performance of the system for individual satellites and which will produce an alarm when performance falls below a predetermined level. That is, an indication will be made if the percentage of observed passes does not conform to the system capability or if a portion of the line appears weak.

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These features of automatic monitoring and on-line operation result in a specialized digital system, the brain consisting of a digital computer to which are connected various input and output devices unique to this operation. The entire integrated system is capable of performing the basic task of detecting noncooperating satellites and of realizing such a detection in a high traffic situation. The traffic situation is rapidly building up to where present manual methods will become impossible, the only solution being complete integrated automation.

In summary, it is important that essentially real time computations be performed which require on-line operation of a computer of adequate capacity, speed, and accuracy to keep current with all satellites in orbit. The Space Surveillance System design concept utilized the computer in a closed loop system wherein received signals, each consisting of many elements, are (a) partially processed by the computer, (b) combined with other receiver outputs to produce tentative observations which are validated by comparison with other received signal characteristics, and (c) then combined to produce a description of the satellite in terms of orbital elements.

* * *

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